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Diesel Engines In-Place Diagnosis of Diesel Locomotives: Modern Approaches and Practical Application

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Abstract

This paper is devoted to research of modern methods for the diesel engines in-place diagnosis of diesel locomotives. In the conditions of intensive operation and growing requirements for the reliability of locomotives, ensuring timely detection and elimination of malfunctions is critically important. A review of modern approaches, such as vibration diagnostics, acoustic analysis, and the use of computer monitoring systems, allows us to assess their effectiveness and feasibility of application in practice. The authors paid special attention to methods of processing information obtained as a result of diagnostics, in particular, the use of neural networks, artificial intelligence, and machine learning to analyze and predict the technical condition of engines. The article also discusses the practical aspects of implementing these methods in rail transport, including technical requirements, economic efficiency, and advantages for the operational reliability of diesel locomotives. The results of experimental studies and examples of successful application of in-place diagnosis methods on real objects are presented.
KEYWORDS: *technical diagnostics, diesel locomotive engines, computer monitoring systems, artificial intelligence, machine learning*

1. Introduction

In the modern world, rail transport continues to be one of the key elements in the system of freight and passenger transport. The operation of railway transport is accompanied by high costs for maintaining its working state throughout the entire period of operation. In the conditions of constant growth in the economic efficiency of maintenance processes, optimization and repair of locomotives are of particular importance. In this context, the task of timely and accurate diagnosis and monitoring of the technical condition of rolling stock becomes critically important for the early detection of emerging malfunctions without the necessity decommissioning of a locomotive and ensuring traffic safety and transportation efficiency [1].

Survival of the operability of rolling stock is ensured by maintenance and repair work, as well as unscheduled repairs, which are carried out to eliminate failures that occur during operation. That is why innovative diagnostic methods that do not require dismantling and disassembling equipment and parts are becoming key elements in strategies aimed at assessing the condition of the diagnostic object, searching for malfunctions and determining their causes, predicting the residual life of mechanisms and determining the terms of preventive repairs without unnecessary disassembling [2]. Innovative in-place diagnosis methods have the potential not only to reduce maintenance and repair costs but also to improve traffic safety.

Diesel plays a key role in ensuring continuous and efficient operation of the locomotive. A diesel locomotive engine is a complex thermodynamic, hydraulic, and mechanical system that provides an efficient and reliable source of energy for movement, especially in cases where electric traction is not practical or economically justified [2].

During operation, the diesel engine withstands intense loads, which eventually leads to wear and failure. And any disassembly of a diesel engine harms its further performance. No matter how carefully the disassembly and assembly are done, the level of restoration of the running-in joints is always different from the initial one. As a result of differences in the deformations of the materials of the parts during secondary assembly, their geometric shape changes, the alignment is broken, etc. This leads to the fact that during the further operation of the diesel engine, the running-in of parts occurs again, which, as is known, is accompanied by an increased wear rate. Secondary running-in takes up to 30% of the operating life of diesel components, which reduces its operational durability [7]. Therefore, timely and accurate in-place diagnosis of a diesel engine is critically important for the prevention of malfunctions and the extension of the service life.

Innovative methods of diesel in-place diagnosis allow not only to detect malfunctions but also to warn them in advance, without the need for dismantling or complete disassembly, which significantly saves time and resources. Modern in-place diagnostic methods are divided into test methods, which involve decommissioning a diesel engine, and functional ones, which involve control without decommissioning it [2].

Functional methods allow you to accurately identify the current state of a diesel engine, evaluate the degree of wear of critical components, and determine the need for repair work since they provide for an individual assessment of the state of a specific diesel engine from the beginning of the functioning to the end of the operation.

2. Analysis of Diagnostic Methods

Methodologies for in-place diesel diagnosis are being developed in various directions, including vibroacoustic diagnosis, diagnosis based on the unevenness of the crankshaft rotation. Each of these methods is aimed at increasing the accuracy and efficiency of fault detection and control of the technical state of the diesel engine.

Vibroacoustic diagnosis of a diesel engine includes methods of analyzing vibration and acoustic signals generated by a diesel engine and its parts during operation. It is based on the fact that any changes in the state of engine parts (wear, backlash, cracks, incorrect adjustment) lead to a change in the vibroacoustic signal, when analyzing this signal it is possible to detect the presence of defects and predict a possible failure.

In [3] it is proposed to use a vibration signal to detect misfires in cylinders. The tests of this method were carried out on the twelve-cylinder diesel engine 2112 SSF of the SU45 mainline diesel locomotive. Determining the parameters of the operating cycle for each cylinder of a diesel engine can help in making the necessary corrections and adjustments to ensure the efficiency of operation, the uniform distribution of the load on the cylinders, as well as the early detection of dangerous trends in the development of malfunctions.

Control of the combustion process based on selected parameters of the vibration signal makes it possible to unambiguously and effectively identify and describe processes occurring as a result of misfiring and can be used as a basis for implementing a diagnostic procedure and identifying defects and malfunctions in fuel equipment and cylinder-piston equipment group.

Test results on a diesel locomotive engine have proven that a vibration signal can be used to record misfiring phenomena occurring during operation. Ignition causes pulsed changes in the amplitude of the vibration signal. The vibration signal is unambiguous in each operating cycle, regardless of the number of cylinders, which confirms the reliability of the method concerning the misfiring detection procedures.

When the load changes, the authors noted changes in the dynamics of the vibration signal. An increase in the load on the diesel led to an increase in the intensity of vibration values in the studied cylinders. The indicators obtained at idle speed were compared with those under diesel load. The analysis of these indicators and their differences confirmed high accuracy in detecting misfiring in cylinders using the vibration method.

However, the method described in [3] also has its drawbacks. This method requires the use of specialized equipment and trained personnel. In addition, although the analysis of the obtained indicators showed high accuracy in detecting misfirings, based on this data alone, it is not always possible to accurately detect all possible failures and malfunctions of the diesel engine.

In works [4,5], it is proposed to use a vibration signal for diagnosing fuel injectors and valve mechanisms, based on applications of magnetic vibration sensors. The tests were carried out on a MAN 6S60MC-C ship diesel engine.

The given method is suitable for use on a diesel locomotive. Analysis of indicator diagrams, based on the study of their shape and consideration of the main parameters, allows identifying the several possible malfunctions of the diesel engine. Such malfunctions include a decrease in the compression ratio, unstable engine operation, improper fuel injection, uneven fuel combustion, etc. At the same time, it should be noted that various types of mechanical and operational malfunctions can lead to similar changes in the form of the indicator diagram, which complicates the diagnosis.

For example, if the diagram shows that the fuel injection occurs later, or the shape of the diagram has changed similarly, this can be a sign of both a late fuel injection angle and wear of the fuel system elements. Also, a decrease in the compression ratio can be caused by other factors: wear of cylinders and compression rings, problems with the tightness of the exhaust valves, or incorrect installation of gas distribution phases. In addition, at the initial stages of the development of malfunctions, there are only minor changes on the indicator diagram, which makes it difficult to detect them. To eliminate this drawback, in [4] it is proposed to record and analyze the indicator diagram and the vibration diagram synchronously.

Using a combination of a vibration sensor with a gas pressure sensor in the cylinders expands the possibilities of diagnosis in contrast to the method given in [3]. A vibration sensor with a magnetic base can determine the moments of lifting and landing of the injector needle, fuel supply by the pump, and opening and closing of the gas distribution valves.

Work [6] proposes a method for determining the mechanical defects of a diesel engine based on noise parameters. This method allows you to monitor the technical state of the engine and, based on the obtained data, generate information about the unit resource.

Research in [6] emphasizes that the processing and visualization of acoustic signals in the form of topological 3D models can significantly improve remote monitoring methods, providing early detection of potential failures and malfunctions.

The work [8] highlights a technique for diagnosing engines based on the results of their indirect display. The method is suitable for use on diesel engines that do not have indicator channels.

The method described in [8] is based on measuring the voltage in the connecting elements of body parts, such as studs and bolts connecting the cylinder covers (heads of cylinder block) and the engine block. The main idea of the method is to use communication elements for the indirect determination of gas pressure in engine cylinders. The choice of communication elements as the object of measurement is based on the fact that they perceive only gas pressure forces and, thus, allow indirect reflection of the engine characteristics.

To implement the method of indirect reflection, a pressure sensor is installed under the nut or mounting bolt of the cylinder head component. When the pressure in the engine cylinder changes, the washer compresses and stretches in the elastic deformation zone, which leads to a change in the resistance of the tensoresistors. These resistance changes are converted into an electrical signal, which, after amplification and analog-to-digital conversion, is recorded by a computer for further analysis.

The research that was carried out in [8] shows that the stretching of studs (bolts) and the compression of washers under them are in the range available for registration by tensoresistors. The analysis of the obtained data allows for receiving indicator diagrams that are informative for assessing the technical state of the engine, its regulation, economy, and environmental cleanliness.

The implementation of the technique proposed in [8] can significantly simplify the diagnosis process, especially on diesel engines that do not have indicator channels for registration of the indicator diagram. However, there are certain technological drawbacks, for example, how to ensure the correct operation of tension sensors under the impact of high loads and temperatures. In addition, it should be noted that different malfunctions can lead to the same behavior on the indicator diagram, as reported in [9]. For example, delayed fuel injection and wear of the fuel equipment lead to the same changes in the shape of the indicator diagram, and a decrease in the percentage of compression can be caused by wear of the cylinders, damage to the piston rings, leakage of the exhaust valve or incorrect setting of the valve timing.

Diagnosing the condition of a diesel engine using the analysis of the unevenness of the crankshaft rotation is based on the measurement and analysis of the frequency of rotation of the crankshaft in different engine operating modes. Using the obtained data, it is possible to determine the characteristic frequencies corresponding to different types of defects and evaluate the degree of their impact on the operation of the diesel engine.

Work [10] proposes to diagnose wear and determine the location of malfunction of the diesel fuel system using the analysis of uneven rotation of the crankshaft.

The process of fuel combustion in the cylinders can be described as periodic explosions, the frequency of which depends on the number of cylinders and the speed of rotation of the crankshaft. If in theory, it is possible to assume the combustion evenness in each cylinder, then in practice, the evenness of fuel combustion in each cylinder is practically impossible, as it depends on many factors. These observations formed the basis of the study of instantaneous angular speed (IAS), which is described in [11]. Despite the fluctuations of the instantaneous angular speed, at the end of each cycle (two revolutions for a four-stroke engine), the average value of the angular speed is the same at both ends of the shaft. Therefore, their comparison can provide information about how the combustion process occurs. Instantaneous analysis of the angular speeds can be used to monitor the operation of the engine since the fluctuations in the angular speeds of the crankshaft directly reflect the gas pressure torque generated by the piston-rod mechanism during the combustion process. The most useful in such an analysis is the assessment of the useful contribution to the operation of the engine of an individual piston.

The tests were carried out on a ship's four-stroke diesel engine with a three-phase generator using special optical encoders. Encoders were installed on both ends of the crankshaft. Data recording starts simultaneously, but the main encoder is the one installed on the free end of the crankshaft, it has an additional groove that allows you to determine the top dead center (TDC). Data from the encoders are sent to the computing module and converted into a laser pulse.

Reference data measurements were obtained only after the diesel engine was adjusted according to the manufacturer's instructions, and were carried out several times to assess the uniformity of the results. Changes in IAS were analyzed using the Fast Fourier Transform (FFT), which revealed the difference in harmonics between the healthy state of the diesel engine and the simulated malfunctions. Between the differences in the amplitude of fluctuations that were detected, their differential value (Δm) was calculated.

The malfunction that was simulated during the experiment was in the form of fuel leakage from the high-pressure fuel pump and the injector clogging. As noted in [10], the obtained results are significantly different from the results that had been obtained on a serviceable diesel engine.

The results of the experiment described in [10] show that the IAS fluctuations of the free and loaded ends of the crankshaft differ. Severe irregularities in the fuel supply, such as a leak from a high-pressure pump, or a decrease in injection pressure, cause significant deviations in the IAS spectrum. The method allows you to detect severe irregularities in the fuel supply, which cause significant deviations in the IAS spectrum but requires the installation of high-precision optical encoders and complex signal processing equipment. This method may be less effective compared to others since the detection of malfunctions that do not significantly affect the angular speed of the crankshaft can complicate the diagnosis of a diesel engine.

In works [12, 13], it is proposed to diagnose a diesel locomotive based on the irregularity of the crankshaft rotation frequency and starting current parameters.

The uneven rotation is explained by the impulse component of the torque in each of the cylinders, as well as the differences between the resistance torque and the variable torque of the engine. The unevenness of shaft rotation is estimated using the degree of unevenness, which is the ratio of the difference between the maximum and minimum angular speeds of shaft rotation to the average angular speed.

The research carried out in [13] is aimed at studying the impact of uneven rotation of the crankshaft on the operation of a diesel engine in its various modes. For this purpose, a 1D12 diesel engine simulation model was created on a 1:1 scale. The created model reflected all the main components and parameters of a real diesel engine. In the course of the experiment, indicator diagrams were analytically modeled for the nominal operating mode of the diesel engine, with reduced pressure and zero fuel supply. Simulating the operation of the diesel engine at different rotation frequencies and loads was performed, which made it possible to study the impact of violations in the operation of individual cylinders on the overall dynamics of the crankshaft rotation. Special attention is paid to the research of the idling mode, as it is the most informative for diagnosing diesel engine malfunctions. As a result of the experiments, it was established that malfunctions of even one cylinder significantly affect the unevenness of the crankshaft rotation.

Measuring the shaft rotation speed, the dependence of which is described in [13], and synchronizing it with the starting current signal according to the order of operation of the cylinders is a key aspect of the method [12]. The crankshaft of a diesel engine is equipped with a sensor that measures the instantaneous angular speed of rotation. Simultaneously, the battery is connected to the sensor that measures the starting current. Data from these sensors are transmitted to the recorder, where they are synchronized using a special synchronization sensor installed on the high-pressure fuel pipe of one of the cylinders. This allows you to get an accurate picture of the operation of each cylinder and determine which one has problems.

This method allows you to clearly correlate the data from each cylinder and identify malfunctions based on the analysis of the unevenness of the crankshaft rotation frequency and changes in the starting current parameters. However, there are certain disadvantages. The main one is the need for accurate synchronization of signals, which may require additional settings and the use of specialized software for data processing. This adds complexity to the implementation of the method and may require additional training of personnel involved in diagnosis.

The comparison of diesel engine in-place diagnostic methods for the internal combustion engine (ICE), their advantages, and disadvantages are shown in Table 1. Based on the analysis, the following conclusions can be drawn: most diagnostic methods are focused on diagnosing the state of the fuel equipment and cylinder-piston group. The considered methods refer to both functional and test diagnostics, while taking into account the difficult operating conditions of a diesel locomotive, it is more expedient to use these methods in the mode of test diagnostics.

Table 1

Comparing methods of in-place diagnosis for the ICE

Method of diagnosis	**Principle of diagnosis**	**Area of use**	**Advantages**	**Disadvantages**
Misfiring detection using vibration signal	Changes in the vibration signal allow the misfiring detection	Fuel equipment, cylinder-piston group	High accuracy of misfiring detection	It requires specialized equipment and trained personnel. It is not always possible to accurately detect all possible failures based on this data alone
Application of a vibration signal to diagnose fuel injectors and valve mechanism	Using a combination of a vibration signal with an indicator diagram	Injectors, valve mechanism	Expanded diagnostic capabilities thanks to a combination of methods. Detection of malfunctions in the early stages	High cost of equipment. Difficulty in realization and high cost of implementation.
Determination of mechanical defects by noise parameters	Analysis of noise signal components	Mechanical system, diverter system of exhaust gases	Early detection of potential failures and malfunctions. Complementing remote monitoring methods	Difficulty in interpreting the results. It requires significant computing resources and specialized software
Diagnosis based on the results of voltage measurements in the connecting elements of body parts	The usage of voltage in the connecting elements of body parts for indirect determination of gas pressure in engine cylinders	Fuel equipment, cylinder-piston group	The possibility of application on diesel engines without indicator taps	Similar changes in the indicator diagram for various malfunctions. Operation of tension sensors under conditions of high loads and temperatures
Diagnostics based on the analysis of the unevenness of the rotation of the crankshaft	Analysis of uneven rotation of the crankshaft to detect wear and determine the location of the fuel system malfunction	Fuel equipment, cylinder-piston group	High accuracy when detecting violations in fuel supply. The possibility of determining the location of the malfunction of the fuel equipment.	It requires the installation of high-precision optical encoders and sophisticated signal processing equipment. Some malfunctions slightly affect the unevenness of the crankshaft rotation
Diagnosis based on the analysis of unevenness of rotation of the crankshaft and starting current parameters	Measuring the crankshaft rotation frequency and synchronizing it with the starting current signal	Fuel equipment, cylinder-piston group	The possibility of detecting malfunctions based on the simultaneous analysis of the unevenness of the rotation frequency and changes in the parameters of the starting current	The need for accurate synchronization of signals.

3. Analysis of Diagnostic Signal Processing Methods

One of the common disadvantages of the considered methods is the difficulty of interpreting the diagnostic results. It is very often to make a diagnosis based on the obtained measurement results one needs to have highly qualified specialists who can perform an analysis of the diagnostic results and predict the further development of the malfunction. In this regard, in addition to the development of new and improvement of existing diagnostic methods, there is the task of developing diagnostic results analysis methods that are as easy as possible to use by service personnel.

Let us consider the methods of processing diagnostic signals, which are used in the diagnostic methods discussed above.

In addition to obtaining a diagnostic signal from the sensors installed on the diesel engine, an important task is the selection of informative component signals and their further processing.

In work [4], the obtained vibration signal underwent filtering of the obtained frequencies and synchronous demodulation of the signal amplitude.

Analysis of the obtained data from the vibro-diagram and the indicator diagram allows you to determine ignition delays and the difference between the geometric and actual moments of fuel injection. Analysis of the vibrations associated with the moment of closing the exhaust valves can provide important information about the state of the gas distribution system in each cylinder of a diesel engine. Synchronous recording and analysis of the indicator diagram and vibro-diagram show good diagnostic results compared to the method from [3].

This technology makes it possible to obtain data on the real phases of valve operation, to detect the moments of "needle lifting" and "needle landing" of the injector during diesel operation, and allows the detection of several malfunctions, even in the early stages, as the vibration signal is supplemented by the signal of the indicator diagram. However, this method also requires the use of high-cost equipment and highly qualified personnel, which increases the cost of implementation.

Modern transport systems are characterized by a large number of information flows from sensors, which complicates their analysis due to the diversity, ambiguity, and non-linearity of the data. Therefore, to overcome such problems, in work [6], it is proposed to use the methods of computer cognitive graphics, which allow to visualization of data in the form of three-dimensional models. This visualization makes it possible to reveal individual features of the structure of noise signals emitted by various elements of the engine. The parametric presentation of information signals in the space of probable dynamic events opens up new opportunities for analysis and remote monitoring of the technical state.

When processing the acoustic signal received from the engine and subsequent differentiation to obtain the first and second derivatives, data on the speed and acceleration of the signal amplitude can be obtained. So, in the "state – speed – acceleration" space, it can be displayed as a dynamic event with coordinates $X(t)$, $dX(t)/dt$, $d^2X(t)/dt^2$. An example of the application of numerical differentiation described in [6] reflects the statistical and dynamic features of the visualization of dynamic events of the digitized engine noise signal.

It is also noted in the paper that engine operating modes affect the appearance of the digitized acoustic signal. The operation of engine mechanisms is accompanied by the generation of acoustic signals of a certain frequency, amplitude, and phase, and if the operating mode is disturbed, or the unit stops working altogether, this, of course, causes changes in the first and second derivatives in the overall engine noise.

However, the implementation of computer cognitive graphics methods for the visualization of noise signals requires significant computing resources, specialized software, and high-cost equipment. Another important aspect is the difficulty of interpreting imaging results. Even with the use of modern methods, the interpretation of three-dimensional models and the analysis of the structure of noise signals can be a complex task that requires specialized knowledge and experience.

The development of artificial intelligence and machine learning methods led to the beginning of the active use of these methods in the processing of diagnostic results. The most common methods are the use of neural networks [14, 15, 19, 20], and machine learning methods (both supervised and unsupervised) [16, 18]. To highlight the most informative components of the diagnostic signal, regression analysis, and dimensionality reduction methods are used in combination with BigData tools [1, 16, 17].

In [14], it is proposed to use neural networks for engine diagnostics. This direction is promising in this field. The paper proposes to use recurrent neural networks, such as the Ellman network, which can generalize engine diagnostic data, to further adjust the model for specific cases. Recurrent networks implement nonlinear methods for modeling complex dependencies in sequential data to control time-varying processes.

In the work, it is noted that Elman's recurrent network is the basis for creating an identifier of the technical state of the engine, the output signals of which and its systems are the operating state, failure of main mechanisms, and failure of control systems. The principle of operation of such an identifier consists in the element-by-element comparison of calculated engine model data with a vector of measured indicators to obtain an error vector, which is fed to the input of a neuro-fuzzy classifier. Such a classifier combines the data processing technique of neural networks and fuzzy logic. The classifier provides data on the health of the engine or its systems, based on the error vector and its time derivatives.

In [15], it is also proposed to use artificial intelligence for diagnostics in the form of multilayer perceptron networks. They are a type of artificial neural networks that consist of many layers of neurons, information in such networks is transmitted from the input layer to the output through hidden layers. Each hidden layer processes information coming from previous layers and performs non-linear operations to interact with the data. This allows multilayer perceptron networks to model complex dependencies between input and output data. Numerical simulations of various degrees of engine misfiring were used to provide sufficient data for training the networks. The simulation models were updated and evaluated using experimental data that were obtained from a test bench where vibration signals were recorded for both the healthy condition and the cases with various faults.

The use of neural networks, which are described in [14, 15], allows for efficient processing of large volumes of data and ensures high adaptability to various engine operating modes. Thanks to the simulation models described in [15], it is possible to quickly train the system on numerical data, which reduces the need for large experimental data sets and allows the simulation of various fault scenarios. However, the main drawback of these methods is the dependence on the quality and accuracy of simulation models, which may not always fully reflect the real operating conditions of the engine. Also, there is a need for significant computing resources for processing and analyzing a large amount of data.

4. Conclusions

Based on the conducted analysis, it can be concluded that modern methods of diesel engine in-place diagnosis of diesel locomotives, in particular vibration diagnostics, acoustic analysis, and computer monitoring systems, significantly increase the efficiency of detecting faults and predicting the technical state of engines. The considered methods of processing information obtained as a result of diagnostics, such as neural networks, and machine learning, show a high potential in increasing the accuracy of diagnostics and reducing the time for detecting faults. These methods allow for analyzing large amounts of data, identifying complex patterns, and making predictions about the technical condition of engines with a high degree of accuracy.

However, it should be noted that the development of diagnostic technologies for locomotive diesel engines requires further research and improvements. An important direction of future research is the development of new methods of analysis of diagnostic data, as well as the integration of diagnostic systems with existing computer systems of locomotive management. In addition, it is necessary to conduct experimental research to check the effectiveness of new methods in real operating conditions.

The implementation of these proposals will provide significant benefits, such as reducing repair and maintenance costs, improving traffic safety, extending the life of locomotive diesel engines, and improving the overall economic efficiency of rail transport. Thus, the further development of methods of diagnosis and processing of results using artificial intelligence is a necessary and promising direction of research.

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